A DRIVING FORCE

DARPA's Research Efforts Lead to Advancements in Robotics and Autonomous Navigation

By J.R. Wilson

From Isaac Asimov's robot stories to R2D2, C3PO, Data, and Cylons, generations have grown up expecting the robots of science fiction to become reality at any moment. Sony's AIBO robot dog and Honda's half-sized humanoid Asimo have only heightened that perception.

But the reality is far more difficult. While Asimo's ability to walk up and down stairs was a breakthrough in robot mobility, DARPA has been pushing the envelope to develop robots able to safely and autonomously navigate a battlefield in combat.

Robots, in one form or another, have been part of DARPA culture almost from day one. During the Vietnam War, the agency worked to improve unmanned aerial vehicles (UAVs) – then known as remotely piloted vehicles – used for low-altitude tactical reconnaissance over enemy territory.

DARPA's work in artificial intelligence (AI) technologies in the 1970s spurred an interest in robotics applications, especially in academia, but the policy at DARPA itself at the time was not to emphasize robotics. Even so, through its Information Processing Techniques Office (IPTO), the agency continued to support robotics research at Stanford and MIT, such as the latter's Machine-Aided Cognition program.

> "What is now called the Future Combat System is basically major robotic additions to ground forces in the field."
> *– Steve Lukasik, DARPA director, 1971-1975*

In the early 1980s, however, DARPA took a more direct role as it began work on a family of autonomous air, ground, and sea vehicles known as the Killer Robots. While never achieving program status, Killer Robots did lay the groundwork for future DARPA work, as did the Strategic Computing program, a major program created in the same time frame to fund all DARPA work in the then-rapidly evolving field of computers.

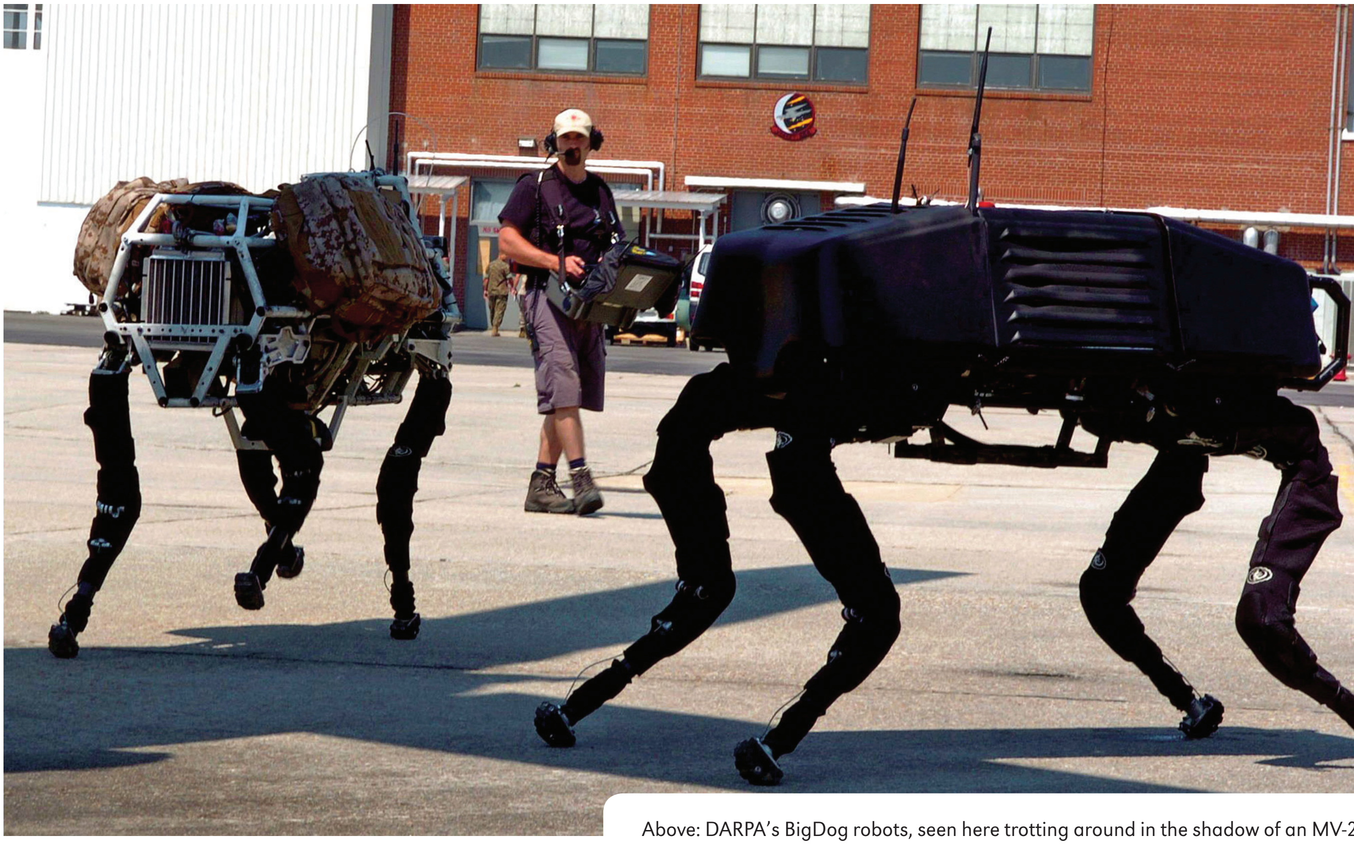
Dr. S. Shankar Sastry, director of DARPA's Information Technology Office (ITO) from November 1999 through February 2001, credits the agency's IT focus for the nation's lead in areas essential to the evolution of both robotics and the supporting technologies necessary for autonomous operation.

"The Strategic Computing Initiative of the 1980s produced its share of disruptive technology in developing reduced instruction set processors, specialized graphics engines, RAID disks, robotics, and AI tools, which are now currently mainstream. The investments by DARPA in these technologies in their early and formative years have paid rich dividends: the U.S. share of the IT-based economy is 50 percent of the worldwide figure of $1 trillion," he said at DARPATech 2000. "More importantly, even in the face of the most recent worldwide surge in the commoditization of IT, it is important to note that DARPA investments have maintained our superiority in national security needs."

In 1985, various DARPA efforts (including Killer Robots) became part of the new Tactical Technology Office (TTO) Smart Weapons program (SWP) to develop a modular family of smart, autonomous weapons. Advances in computer technology and software (such as Automatic Target Recognition) were believed to finally have made a true autonomous loitering weapon possible.

The size, weight, power demands, and capability of computers had been perhaps the greatest limitation on reality catching up with fiction in the operation and navigation requirements of military robots, whether in the air, on the ground, or at sea.

"Before the late 1980s, computers were basically too large to fit on a vehicle, so the technology required at least something down to the PC



U.S. Marine Corps photo by Lance Cpl. M. L. Meier

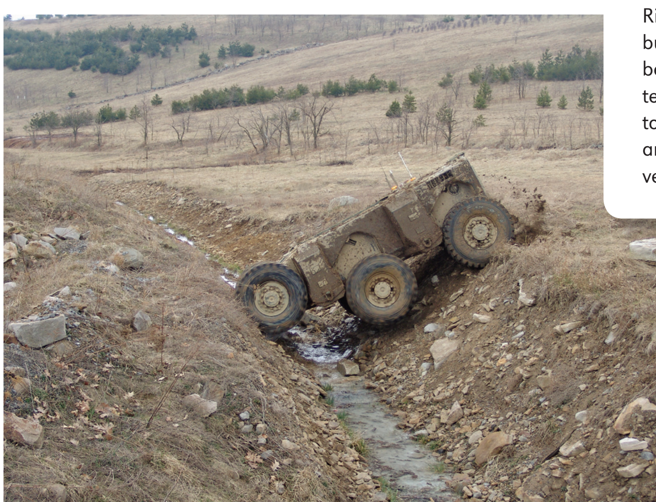


Photo courtesy of Carnegie Mellon University Robotics Institute

Above: DARPA's BigDog robots, seen here trotting around in the shadow of an MV-22 Osprey while given commands via remote control at Marine Corps Air Station New River, N.C., June 26, 2006, could carry extra gear to free soldiers and Marines of the burden of extra weight. Below, left: The Crusher unmanned ground vehicle (UGV) is being developed under the DARPA/Army UGCV-Perception for Off-Road Robotics Integration (UPI) program. Crusher is a highly mobile vehicle designed from the outset to be unmanned. It is being equipped with state-of-the-art perception capabilities, and will be used to validate the key technologies necessary for an unmanned ground vehicle to perform military missions autonomously.

level," notes Larry D. Jackel, DARPA program manager for unmanned ground vehicles (UGVs) from 2003 to 2007. "DARPA took a lead role in funding those efforts and it probably wouldn't have happened in the U.S. had DARPA not done that."

Those advances were the foundation for SWP's Autonomous Air Vehicle (AAV). Precursor to today's smart cruise missiles, the AAV incorporated Automatic Smart Route Planning, using SCI-developed software to update its route, mission, and target in flight, factoring new data transmitted from outside resources as well as its own sensors and monitored fuel supply. To that was added autonomous search strategies able to build on advanced route-planning algorithms that merged the pre-flight mission plan with in-flight updates.

While successes in the first and second Gulf wars put the spotlight on UAVs, DARPA also has been working on the far more difficult task of developing UGVs. Achieving success on the ground is multifaceted, from truly autonomous navigation to determining which approach best meets mission needs – wheels, tracks, or legs, each with its own set of problems and requirements.

"In the work I did on UGVs, the one thing that was key was dealing with unstructured environments and perfecting that," Jackel says. "How do you deal with really rough off-road terrain? Soldiers are very nimble – they can climb over obstacles, go through narrow gaps, etc. A wheeled vehicle can't do that; for a wheeled vehicle to be stable, the wheelbase has to be wider than the height of the wheels, so you can't get into a narrow environment or traverse laterally on a hillside – it will just roll over.

"If you have a vehicle with legs, you can better accommodate irregular terrain and can have a much narrower stance and adjust the height

Eric Krotkov, DARPA's UGV program manager in 1997-1998, helped refocus the concept of autonomous ground robots by bringing to the military effort a decade of experience working on planetary rovers for NASA.

DARPA photo

of the legs. You also can move the legs around or over obstacles, so there are a lot of things you don't have to worry about. But you also have to do a lot more planning. You have limited choices where you can put a wheeled vehicle, but the possibilities are so much larger with legs, you have to do a bigger search and determine where to use them."

Two DARPA offices are funding the development of four-legged walking robots being built by Boston Dynamics.

The Defense Sciences Office's BigDog is a little more than 3 feet long and 2 feet high and can carry nearly 75 percent of its own 165-pound weight. The computerized, gasoline-powered quadruped's articulated, shock-absorbing legs enable it to trot at 3.3 mph, climb a 35-degree slope, and maneuver across rough terrain. Its internal sensor package includes a laser gyroscope and stereo vision system and monitors joint position and force, ground contact and load, engine and oil temperatures, and hydraulic pressure.

Locomotion research is the primary focus of the IPTO/Boston Dynamics LittleDog robot. Three small electric motors power each of its four legs and can operate continuously for up to 30 minutes before its lithium-polymer batteries need recharging. LittleDog is being used to examine the fundamental relationships involving motor learning, dynamic control, environmental perception, and legged movement across rough terrain. Its onboard computer handles actuator control and communications and monitors joint angles, motor currents, body orientation, and foot/ground contact.

Size also is an issue, requiring advances in – and trade-offs between – materials, power sources, computers, sensors, etc.

"We worked on developing technologies that would let a walking vehicle go over very rough terrain, but a quadruped is a difficult challenge; legged vehicles have greater potential, but also more extreme control issues," Jackel explains.

"There is no real limit on how large a UGV can be, but on the other end, it has to have some kind of power pack and mobility, computational capability, and communications. The smaller you make it, the bigger an issue terrain and power become; the larger you make them, the more difficult it becomes regarding objects and people around them. But we built things the size of an SUV, which was workable; the size of a tank or even a tractor-trailer truck also is possible – or you could make something down to around 1 foot."

Autonomous navigation also is simpler for a wheeled vehicle, in most respects, in large part due to the limitations of where it can operate. Approaches to navigation have ranged from cameras providing two-dimensional information to the "bump-and-change-direction" approach taken with toys and floor sweepers. On a battlefield, however, something far more sophisticated is required, especially for a walking robot trying to step over, around, or through an obstacle.

"There are numerous goals. One is to have a vehicle that can safely drive down the street by itself, avoiding objects including moving people and animals. We're pretty far from that right now. Another is a vehicle that could go off in an area where there are no other moving objects – and we're relatively close to that. Another is something that could approach an IED [improvised explosive device] and, with assistance from a human operator, defuse it," Jackel explains. "As these things become better and cheaper, the opportunities extend.

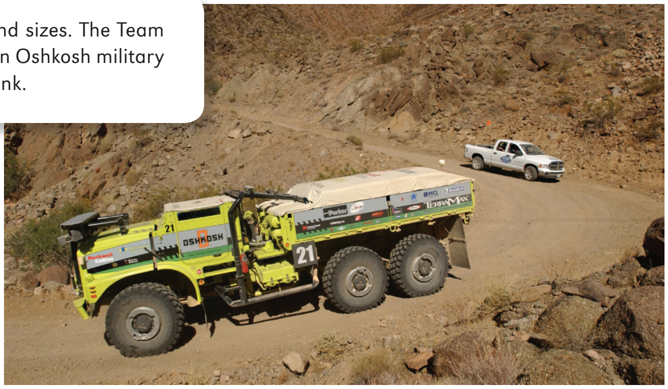
"Generally, you want vehicles to go places too dangerous for a person – such as travel in environments with chemical, biologic, or radiological hazards – or where the job is extremely boring. So it might drive somewhere, then set on a hill for a week doing overwatch and only have a moment of real action. You wouldn't want to have to supply a team of people with the support to do that 'round-the-clock."

Some ideas have turned out to be more difficult than expected when tested by DARPA – and less likely to see real-world implementation for several more years. One example is a robotic combat ambulance that could, either by itself or with human assistance, locate a wounded warfighter, load him or her into an armored carry space, and autonomously transport the patient to the nearest medical help.

"The vehicle has to have common sense, which they don't have. If you think about having to deal with the unexpected, we don't really have software yet to do that. People are working on it, but it will be a

"In nature, advanced animals learn to control their bodies; our plan is to find ways to have robots learn control."
– Larry Jackel, UGV program manager, 2003-2007

Autonomous vehicles during the 2005 Grand Challenge came in all shapes and sizes. The Team TerraMax entry, shown here on a winding section of the course, was based on an Oshkosh military truck. UGVs of the future could range in size from a breadbox to an Abrams tank.



while," Jackel says. "So for battlefield evacuation, if everything was prescripted and went according to plan, it would be great – but battlefields tend to be brutal.

"Right now, the bigger operations are things where you don't have to deal with humans, as passengers or side-by-side. So if you wanted to do route recon, that would be a good mission for a UGV, as would surveillance. Even resupply. But doing evacuations, while not out of the question, would be difficult for now."

Eric Krotkov, DARPA's UGV program manager in 1997-1998, helped refocus the concept of autonomous ground robots by bringing to the military effort a decade of experience working on planetary rovers for NASA. Much of DARPA's previous work had involved large vehicles, some the size of tanks, and had successfully addressed the technical requirements and specifications to the point where they could be spun off to the development community. Krotkov saw this as the perfect opportunity to begin looking at much smaller robots.

"I thought the [planetary rover] technology was promising and NASA was doing what they could, but DARPA was the place to develop the idea of smaller vehicles for military applications," he said. "I spent the majority of my time formulating a new program that ultimately would be called Tactical Mobile Robotics [TMR]. TMR's primary goals were to make it mobile for urban terrain, fit into a backpack, and travel 100 meters per operator intervention. So it was an order of magnitude smaller and an order of magnitude smarter. We came through on the mobility part pretty well and got things moving in the right direction on autonomy."

As the Special Operations Command representative to DARPA, Army Lt. Col. John Blitch had pushed SOCOM's interest in small robotics – ground, air, and underwater – in portable formats that could fit into areas a human could not – areas that would be left unguarded by the enemy in an urban environment. Blitch took over as program manager for TMR when Krotkov left in 1998, further focusing on the operational needs of small-unit warfighters.

"I would separate the objectives of the program into the operational objective and the enabling technology objective," he says. "The operational focus was to revolutionize urban warfare by penetrating denied areas with robots. You can deny access in a lot of ways: politically by not allowing troops into a country, simply by booby traps and barbed wire fences and by physical intervention in terms of weapons. My objective was to build robots that could penetrate a denied area and then operate effectively in ways that would be valuable to DoD [the Department of Defense]."

Blitch says the intent was to meet six primary imperatives – general performance objectives that, based on operational experience, were crucial to making a tactical robot functional enough to survive on the battlefield:

1. Response to lost communications – The robot should not simply continue the last command, but should try to re-establish a link.

2. Tumble recovery – The robot must be invertible so that even if it is blown into the air by a mine and lands on its back, it can continue moving, even upside down, and change its center of gravity or leverage itself if it lands on its side.

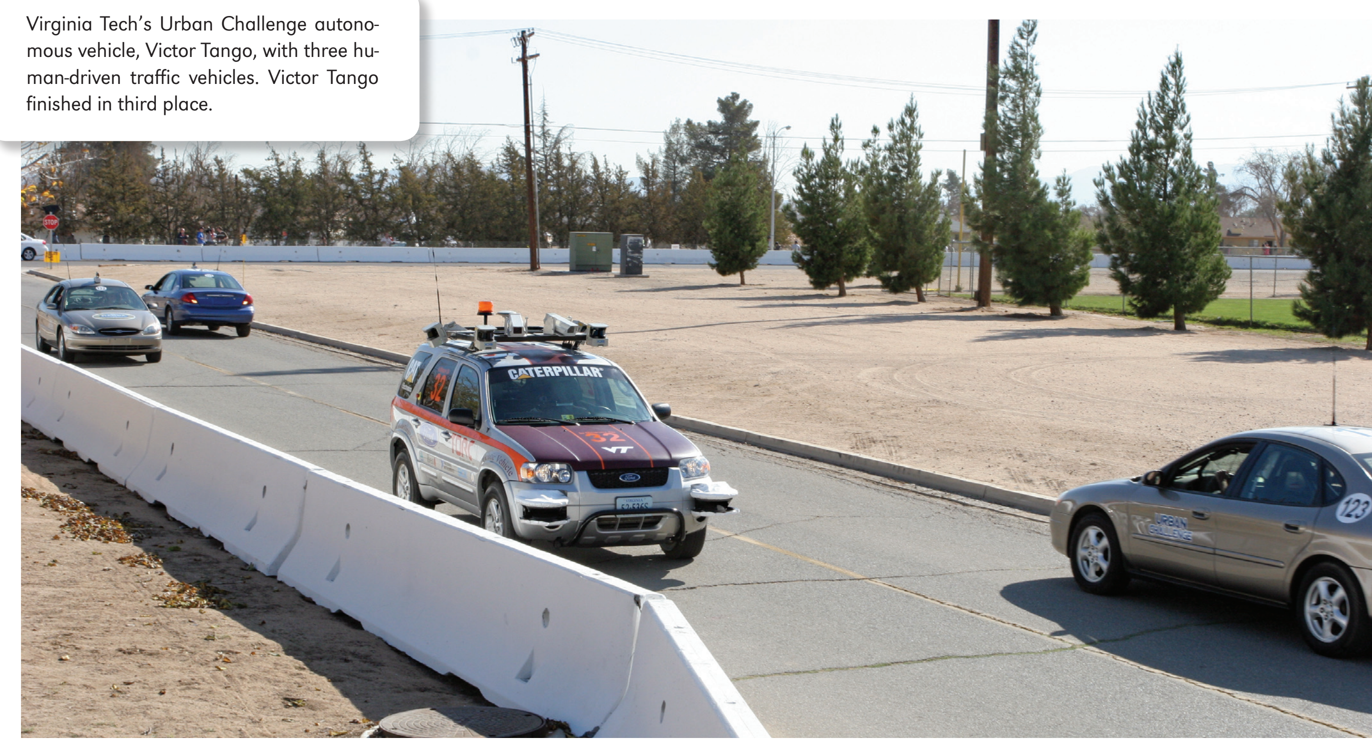
3. Anti-handling – The robot must feature a method of keeping the enemy from picking it up while not endangering innocent civilians, especially children. These means remain classified, but generally fell into two categories: prevent capture or, if captured, self-destruct in a non-violent manner (such as frying the internal electronics).

4. Self-location – The robot should fuse GPS, odometry, and visual inputs to determine its location inside a building.

5. Complex obstacle negotiation – The robot must be capable of such activities as stair-climbing, or moving through mud/rubble/bushes; this required hybrid mobility, a combination of wheels, tracks, and legs to avoid any single point of failure.

> "There has been a lot learned about the whole issue of robotics and mechanical walkers [and] they all contribute to the store of knowledge – sometimes they're worthwhile and some of them are crazy."
> *– Larry Lynn, DARPA director, 1995-1998*

Courtesy of Lockheed Martin



Virginia Tech's Urban Challenge autonomous vehicle, Victor Tango, with three human-driven traffic vehicles. Victor Tango finished in third place.

DARPA photo

"Vehicles competing in the Urban Challenge will have to think like human drivers and continually make split-second decisions to avoid moving vehicles, including robotic vehicles without drivers, and operate safely on the course. The urban setting adds considerable complexity to the challenge faced by the robotic vehicles, and replicates the environments where many of today's military missions are conducted."

– Dr. Norman Whitaker, Urban Challenge program manager

6. Self-cleaning – The robot must have the ability to clear dust, mud, or anything else that might block a camera lens.

When Blitch retired in June 2001, DARPA loaned him most of the 43 TMR prototypes it had built so he could continue his work privately. Before he could do so, however, terrorists attacked on September 11 and he took some of the TMR robots to New York City for use in search and rescue efforts. By January 2002, he and the robots were in Afghanistan, searching caves for booby traps before Special Operations troops entered them.

Today there are hundreds of TMR robots – PacBots and Talons – throughout Southwest Asia, none meeting all of the original imperatives but still highly regarded by warfighters dealing with booby traps, car bombs, and IEDs.

"For the last 30 years of DoD investment in robotics, before TMR, no one had really done anything for the grunt. And while it still isn't at the level I want it to be, they finally have done something to benefit the individual soldier and Marine," Blitch says. "So TMR refocused the DoD robotics world on small platforms for the dismounted troop – and in that sense, it was a success."

In addition to Blitch's six imperatives, Krotkov says a major requirement for DARPA robots was sensors.

"In the early-to-mid '90s, a German company developed a laser curtain that, if pierced, would shut down robots doing dangerous industrial work. It turned out those also could be put on a mobile robot and, instead of pointing from the ceiling to the floor, could look out, down a corridor. So for the first time, you could buy a $5,000 sensor giving good conceptual data instead of visual systems that were a bit flaky or used huge, exotic laser rangefinders that really could not be put on a manageable-size vehicle," he says.

"This was fast, cheap, small, and gave sensor data the R&D community could use to do the planning on where to go next, obstacle avoidance that allowed robots to go down halls, make maps, avoid things, and look pretty smart. But even stupid algorithms running with good sensor data could do reasonable things."

While rapid advances in computer technology in the 1990s and beyond resolved many of the "processing power per mass" concerns for UGVs, Krotkov says another problem still remained.

"That is just the hardware side of it; there is a conceptual side that is equally or even more challenging. You can't field a system and have it driving around unless you have processing systems and power supplies of the proper scale, but theories on how to process data and turn it into useful information on the environment and how to get from point A to point B and decompose data into manageable chunks also [were] missing," he says.

The algorithms to address those issues also began to emerge in the 1990s, advancing substantially in the first decade of the new century. The resulting combination of hardware and software solutions, Krotkov believes, has paved the way for an evolutionary path toward true autonomous navigation and operations.

"Autonomous navigation is equally applicable to any type of robot vehicle. The classical description is sense-think-act: You take the sensor data in that tells you about the environment around the robot; you think – perception turning the sensor data into symbolic, useful information and planning what to do next; then act, turning it into commands to actuators, whether that is turning a wheel, moving a leg, adjusting a wing or jet or prop rotation rate in the water," he explains. "So the sense-think-act model applies to anything, at any scale, from inside the human body to the size of a cargo ship, and any medium – outer space, in the air, on the ground, under the ground, on or under the water, in ice, even in various chemicals."

Others also were taking note of DARPA's progress. In 2005, for example, the Army leveraged a number of technologies from DARPA's Mobile Autonomous Robot Software (MARS 2020), PercepTOR (Perception for Off-Road Robotics), and Future Combat System-related robotic programs for its Unmanned Autonomous Collaborative Operations, in which UAVs and UGVs were tasked to work together, without human guidance.

"It becomes hard-squared to do both, because both the UAV and UGV have to be working together. You have to worry about the UGV running into people, and about the UAV, which is noisy, giving away its position and, if the environment is windy, the UAV becomes difficult to operate. So coordinating the two becomes problematical," Jackel says.

DARPA took a new approach to pushing UGV and autonomous navigation technology in 2004 with the Grand Challenge – an open invitation to any individual or group, whether private or from industry or academia, to equip a car to drive itself across a 142-mile stretch of desert near Barstow, Calif. No one completed the course, but the idea gained considerable public support.

Eighteen months later, DARPA held another Grand Challenge, with a $2 million prize to the first participant to finish a 132-mile route in less than 10 hours. With the learning experience of the first race and 18 months to develop, five vehicles out of 195 applicants completed the course – four within the time limit. The prize went to a team from Stanford University, whose car averaged 19 mph.

"The two Grand Challenge events succeeded in inspiring scientists and engineers from around the country to find new solutions to a tough technical problem," says Ron Kurjanowicz, the 2005 Grand Challenge program manager. He adds, "In a relatively short period of time they made remarkable progress in the areas of sensors, algorithms, and autonomous ground vehicle systems integration. Technical achievement relies on new ideas, and the Grand Challenge events acted as catalysts for many such ideas, particularly in computer science."

"It was a very difficult course for totally autonomous vehicles; always turning, sometimes hairpin turns with obstacles," current DARPA Director Dr. Anthony J. Tether told attendees at DARPATech 2007. "The vehicles were allowed only two commands: start and stop.

"But DARPA, as usual, was not satisfied. After all, the obstacles were fixed. So we

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created a new challenge – the Urban Challenge – because in the real world, the autonomous vehicles would be confronted with traffic. The winning vehicles must drive 60 miles in city-like traffic in under six hours, as well – or better – than a licensed driver."

On Nov. 3, 2007, a field of 11 challengers (out of 89 original entries) set out across a 55-mile network of roads at the former George Air Force Base in Victorville, Calif., now used by the U.S. military to train for urban operations. The course effectively simulated the type of terrain in which American forces operate overseas, with each vehicle required to obey all California traffic laws while merging into traffic, navigating traffic circles, and safely passing through intersections. The vehicles' onboard computers made split-second decisions, demonstrating safe autonomous operation in both urban traffic and less populated areas.

First place – and a $2 million prize – went to Carnegie Mellon University's Tartan Racing, which averaged about 14 mph. A $1 million second-place prize went to the Stanford University team that won the 2005 Grand Challenge, while Virginia Tech's Victor Tango team claimed the $500,000 third prize. Also finishing were the Ben Franklin team (University of Pennsylvania, Lehigh University, and Lockheed Martin), Cornell University, and MIT.

"DARPA is an interesting organization," Tether commented after the race. "We really never finish anything. All we really do is show that it can be done. We take the technical excuse off the table, to the point where other people can no longer say, 'Hey, this is a very interesting idea, but you know that you can't do it.' I think that we're close to that point, that it's time for this technology to [be furthered] by somebody else."

DARPA also has been involved with the Navy at various times on how robotic technology might be applied to surface and subsurface robots, from unmanned underwater vehicles (UUVs) to unmanned surface vehicles (USVs), such as a fully robotic arsenal ship proposed by the chief of naval operations (CNO) in the mid-1990s.

"That was a case of the Navy trying to make good use of ARPA," recalls Larry Lynn, who served as DARPA's director from 1995 to 1998. "One of my drivers was to get rid of everybody [on the ship]. There was a favorite story a lot of people told: that we were going to put a man and a dog on there – the man to feed the dog and the dog to bite the man if he did anything."

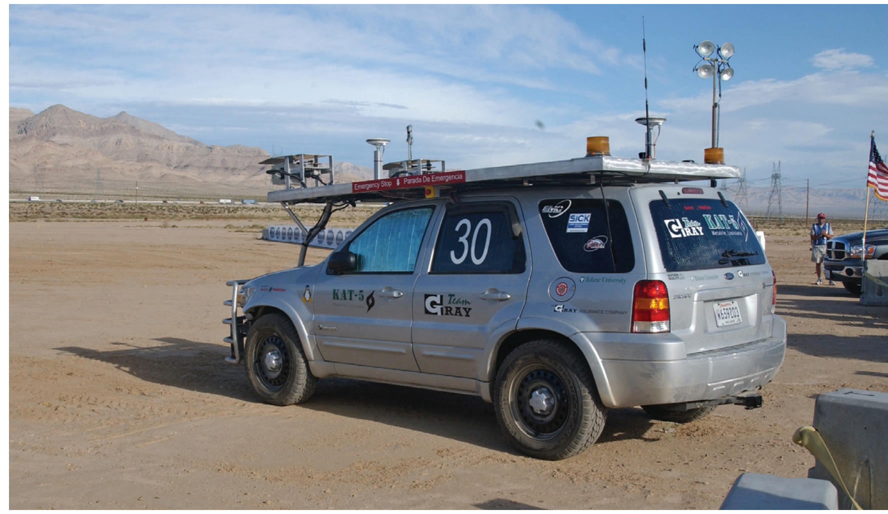
The project was scrapped by the Navy and Congress when the CNO, Adm. Michael Boorda, died. But the concept of dramatically reducing the number of sailors aboard ship by increasing the level of automation was incorporated into the Littoral Combat Ship, a 417-foot, 3,000-ton, multi-mission platform with a crew of 40 that was launched in 2006.

"We're getting there," Lynn contends, "and one day we will have a several-thousand-ton ship going around with nobody in it."

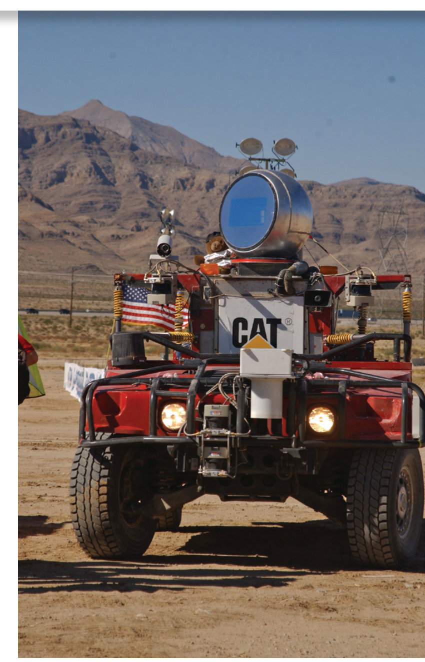
DARPA also is taking autonomous navigation and operations to space, from work on planetary rovers that cannot rely on human controllers millions of miles (and hours or days) away, to its most recent success, Orbital Express, in which two satellites in low-Earth orbit rendezvoused, mated, and exchanged fuel and components, all without human interaction.

Lessons learned from those DARPA programs will find their way into autonomous navigation programs for terrestrial UAVs, UGVs, UUVs, and USVs, as will other DARPA research, both directly and indirectly related to robotics, that will ultimately advance the technology and capability.

"The real figure of merit here is not how autonomous is it, but how autonomous [is it] per dollar of programming or line of code or human effort? Just as you want the robot to be autonomous, you want it to learn from its experiences and not have a human do all that tedious programming," Krotkov concludes. "So it is autonomous capability divided by programming effort. That's what we need to improve; have the numerator of that fraction go up – more autonomy – but more importantly, have the denominator go down – the same level of capability for a lot less programming."



Above and below: Two contenders in the 2005 DARPA Grand Challenge. The Grand Challenges and most recent Urban Challenge brought together some of the best minds and concepts in the country and produced fresh ideas in developing autonomous ground vehicles.



DARPA photos